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Composition of chromites in cordierite- and mica-bearing Cr–Ni ores from Málaga Province, Spain

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SUMMARY. An unusual paragenesis of chromite, nickeline, cordierite, and red-brown mica occurs in veins, pods, and schlieren in serpentinized ultramafic rocks at La Gallega and Los Jarales in Málaga province, Spain. The chromites in this paragenesis are low-ferric, ferrous-rich aluminous chromites with exceptionally high vanadium content ranging between 1·8 and 2·9 wt % V_2O_3 and high zinc content ranging between 0·5 and 1·0 wt % ZnO. A comparison of chromite composition with available experimental data, together with paragenetical and textural evidence, suggests that the chromite, cordierite, and red-brown mica crystallized at magmatic temperatures between approximately 1300° and 1000 °C at low oxygen fugacities and maximum pressures below 10 kb, probably near 5 kb.

SAMPLES of chromite–nickeline ores, collected from dumps at the abandoned mines of La Gallega near Ojén and Los Jarales near Carratraca, Málaga province, S. Spain, show an unusual paragenesis with chromite, (Ni, Fe, Co)-arsenides and -sulpharsenides, cordierite, red-brown mica, plagioclase, chlorite, and serpentine. The ores typically form bronze-coloured rocks, consisting of fine-grained mixtures of chromite and Ni-arsenides, which occur associated with cordierite and the other silicates in schlieren, pods, and veinlets in serpentinized ultramafic rocks of the alpine type (Gillman, 1896; Hernandez-Pacheco, 1967; Dickey, 1970). According to Hernandez-Pacheco (1967) at La Gallega the ore schlieren and veinlets are found in serpentinized pyroxenitic dykes in the mainly harzburgitic ultrabasic massif, which locally also contains cordierite veinlets with accessory orthopyroxene, chromite, and nickeline.

The first author is responsible for the text of this paper, which describes the chromites in the peculiar ore type. The Ni-arsenides and -sulpharsenides have been described earlier (Oen, Burke, Kieft, and Westerhof, 1971, 1972), while paragenetic relations and petrogenesis are discussed more extensively in a paper by Oen (1973). Electron microprobe analyses were done by the second author with a Cambridge Instrument Co. Geoscan operated at acceleration potentials of 20 and 25 kV. For the determination of Cr, Fe, Ni, Co, and Zn pure metal standards were used, for V, Ti, Al, Mn, Mg, Na, and Si standards of synthetic V_2O_5 and TiO and of corundum, rhodonite, periclase, albite, and quartz, respectively. Results were corrected according to a computer program adapted from Springer (1967) with some modifications. For microprobe facilities the authors are indebted to Professor W. Uytenbogaardt, Free University at Amsterdam, and to the WACOM, a working group for analytical geochemistry subsidised by the Netherlands Organisation for the Advancement of Pure Research (ZWO). X-ray diffraction analyses were done by the third author.

Description of samples

Polygonally textured chromite aggregates. The chromite–nickeline rocks of La Gallega consist for 80 vol. % or more of fine-grained chromite in polygonally textured aggregates of often five- or six-sided chromite grains, usually less than 0·3 mm across, with straight or slightly curved boundaries often meeting at triple points (fig. 1 in Oen, Burke, Kieft, and Westerhof, 1971). Nickeline with some löllingite and gersdorffite, red-brown mica, cordierite, chlorite, and serpentine occurs in the interstices between the chromite grains and as fracture fillings in broken and pulled-apart grains of chromite.

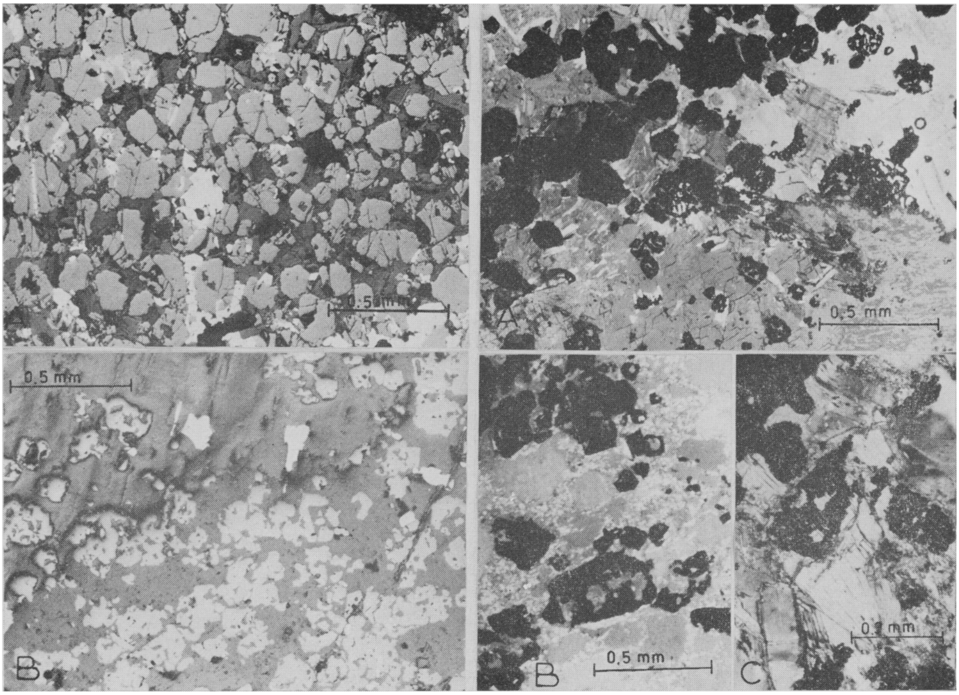
Similar polygonally textured chromite–nickeline aggregates occur at Los Jarales, but here the nickeline is accompanied by maucherite. Furthermore, the chromite appears more intensely fractured and pulled apart. Often the Ni-arsenides and an increased amount of red-brown mica, cordierite, and plagioclase occupy wider intergranular and intrafractural spaces in the chromite aggregates (fig. 1*a*), reducing the chromite to only 60–80 vol. % of the rock. The chromite grains often appear inhomogeneous with irregular rims and patches of different reflectivity.

Skeletal and euhedral chromite crystals and aggregates. At Los Jarales the polygonally textured chromite aggregates occur associated with thin veins, streaks and pods rich in cordierite, red-brown mica, and plagioclase and containing varying amounts of skeletal and euhedral chromite crystals. The chromite skeletons often show an outer frame defining the octahedral outer form and enclosing an octahedral network of chromite lamellae (fig. 2). The skeletons of chromite occur embedded in aggregates or enclosed in crystals of red-brown mica, cordierite or plagioclase (oligoclase to bytownite). These silicates often occur as coarser grained, partly recrystallized crystals containing inclusions of skeletal and euhedral chromites in a poikilitic fashion (fig. 1*b*).

Skeletal chromites resembling the ones described here have been described from orbicular and nodular chrome ores in alpine type peridotites (e.g. Thayer, 1969); the skeletal habit of these chromites is mostly ascribed to magmatic resorption (Donath, 1962; Kern, 1968; Thayer, 1969). However, resorption cannot explain the skeletal chromites of Los Jarales for three reasons:

In contrast to the polygonal chromites, which always show fracturing, pulling apart and filling of fractures with silicates and arsenides, the chromite skeletons and euhedral crystals are unaffected by fracturing (compare figs. 1*a* and 1*b*). Locally, chromite skeletons are found across deformation kinks in mica (fig. 2*c*) and recrystallization boundaries in aggregates of mica, cordierite, or plagioclase. Obviously, these skeletons have formed in an already recrystallized and fractured solid matrix.

The chromites contain crystallographically oriented very fine exsolution lamellae of what is probably rutile. The orientations of these lamellae indicate that in the polygonally textured aggregates adjacent chromite grains are dissimilarly oriented, as is generally the case in recrystallized granoblastic aggregates. On the other hand, the orientation of exsolution lamellae in chromite skeletons and of the lamellar directions of the skeletons themselves indicate that these skeletons often show a uniform or nearly uniform crystallographical orientation over large areas. This suggests that the skeletons have formed by a kind of oriented growth in an already recrystallized matrix.



FIGS. 1 and 2: FIG. 1 (left). (*a*), top. Partly recrystallized poikilitic red-brown mica enclosing a groundmass of broken and pulled-apart chromite grains; pulled apart fractures in chromite filled with the mica and nickeline (white). (*b*), bottom. Poikilitic crystals of red-brown mica enclosing undeformed skeletons of chromite. Reflected light. FIG. 2 (right). (*a*), top. Chromite skeletons embedded in fine-grained mica (white, centre of figure), enclosed in plagioclase (below centre of figure), and across silicate boundaries (right of centre of figure). (*b*), bottom left. Chromite skeletons in altered cordierite aggregate. (*c*), bottom right. Skeletal chromite across deformation kink in mica. Transmitted light.

The polygonal chromite grains never exceed 0·5 mm in diameter. Individual chromite skeletons frequently are over 0·5 mm across and occasionally reach 1·0 mm in diameter.

The skeletal and euhedral chromites are thus believed to have formed after the recrystallization of earlier chromite and the fracturing of the recrystallized grains in the polygonally textured chromite aggregates. The latter aggregates are locally traversed by thin discordant dilatation veinlets containing cordierite and some skeletal and euhedral chromites.

Chromite in cordierite rocks of La Gallega. At La Gallega the chromite–nickeline rocks often occur in sharp contact with coarse-grained cordierite rocks containing accessory chromite, sometimes with skeletal habit, and nickeline. Occasionally, cordierite crystals show two or more zones, apparently growth zones, full of very fine chromite inclusions.

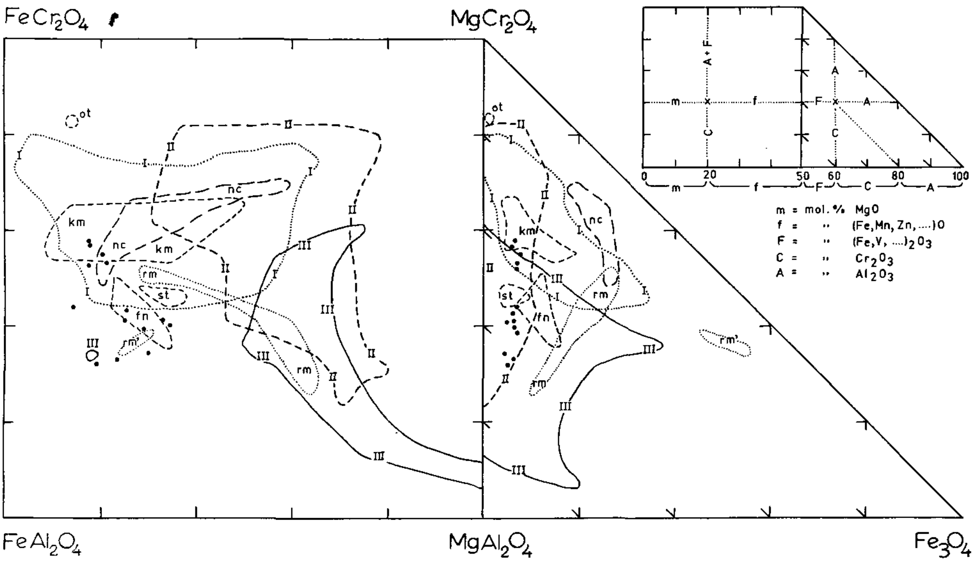


FIG. 3. Chromites from La Gallega and Los Jarales (dots) compared to chromites from other deposits. Inset shows method of plotting a chromite $(Fe_{0.6}, Mg_{0.4}) (Cr_{0.4}, Al_{0.4}, Fe_{0.2})_2 O_4$ in mol % of its five oxide components. Chromites from ores and rocks in layered intrusions plot within the areas bounded by dotted lines: I—chromites from Bushveld (van der Walt, 1942), Selukwe (Cotterill, 1969), Great Dyke (Bichan, 1969), Stillwater (Jackson, 1969; Stevens, 1944; Sampson, 1969; Thayer, 1969); rm, rm′—Rhum layered intrusion (Henderson and Suddaby, 1971). Chromites from alpine type ultramafic and podiform chrome ores plot within the areas bounded by broken lines: II—chromites from Mt. Albert (MacGregor and Smith, 1963), Andızılık-Zımparalık (Engin and Hirst, 1970), several localities in India (Malhotra and Rao, 1963), N. and S. America (Stevens, 1944), Kempirsay (Pavlov and Chuprynina, 1967); nc—New Caledonia (Guillon, 1970); ot—Outokumpu (Thayer, Milton, Dinn, and Rose, 1964); km—Kemi (Vaasjoki and Heikkinen, 1962); st—Sitampundi (Malhotra and Rao, 1963; Subramaniam, 1956); fn—Fiskenaesset (Ghisler and Windley, 1967). Chromites from ultrabasic nodules in basalts and kimberlites plot within the area bounded by full lines, III (Ross, Foster, and Myers, 1954; Ukhanov, 1970; Frisch, 1971).

Composition of the Chromites

All chromites from La Gallega and Los Jarales have exceptionally high vanadium content, ranging between 1·8 and 2·9 wt. % V_2O_3 (table I). The average mol. % V_2O_3 is 1·4 and equal to the average calculated mol. % Fe_2O_3; both the V_2O_3- and Fe_2O_3-content show little variation with the Cr_2O_3/Al_2O_3 ratio (fig. 4). Vanadium in chromite in general rarely exceeds 0·2 wt % V_2O_3 and other chromites with 1·0–3·0 wt % V_2O_3 are known only from Outokumpu, Finland (Weiser, 1967b).

Besides some MnO, NiO, and CoO, the chromites from La Gallega and Los Jarales show unusually high ZnO-content, between 0·5 and 1·0 wt %. This is equalled by chromites from only a few other occurrences, among which is Outokumpu, Finland (Donath, 1962; Weiser, 1967a, b).

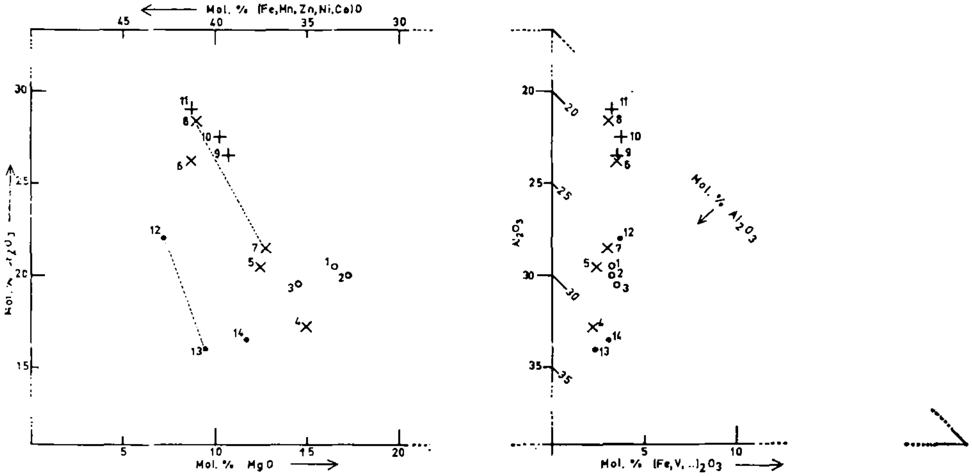


FIG. 4. Chromites from La Gallega and Los Jarales; the diagram is an enlargement of the relevant portion of Fig. 3. Numbering of analyses corresponds to Table I: 1, 2, and 3 (open circles) chromites in polygonally textured aggregates, La Gallega; 4 to 8 (×) chromites in polygonally textured aggregates, Los Jarales; 9 to 11 (+) skeletal and euhedral chromites, Los Jarales; and 12 to 14 (dots) chromites in cordierite rocks, La Gallega. Broken lines connect analyses of different portions of same grain.

The chromites from La Gallega and Los Jarales have a rather distinctive low-ferric, aluminous, ferrous-rich composition compared to chromites in layered intrusions, ultramafic nodules in basalts and kimberlites, and alpine type ultramafics (fig. 3). In the latter class a few deposits (Fiskenaesset, Greenland; Sitampundi, India; Kemi, Finland) contain chromites of almost similar bulk composition to the ones described here.

Electron microprobe analyses of the homogeneous chromite grains in polygonally textured chromite–nickeline rocks of La Gallega show only slight variations (table I, fig. 4, analyses 1, 2, and 3). These chromites show low Cr_2O_3/Al_2O_3 ratios and high MgO/RO ratios compared to the other textural or paragenetical chromite varieties; their unit cells have a 8·224±0·002 Å to 8·237±0·002 Å with a mean value of 8·226±0·002 Å.

The chromites in cordierite rocks of La Gallega generally show lower Cr_2O_3/Al_2O_3 and MgO/RO ratios than those in polygonally textured chromite–nickeline rocks from the same locality (table I, fig. 4, analyses 13 and 14). In general the chromite and associated cordierite show little variation in composition. The cordierite is a Mg-cordierite

TABLE I. *Representative microprobe analyses of chromites, La Gallega and Los Jarales. Wt % metals calculated into wt % of corresponding oxides;* Fe *calculated into* FeO *and* Fe_2O_3 *on the assumption that* $RO = R_2O_3$ *and that* TiO_2 *in* R_2O_3 *sites is compensated by a corresponding amount of* FeO

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Cr_2O_3	33·4	32·6^5	31·4^5	28·6^5	32·9	39·7^5	34·3^5	43·2	40·4	42·0^5	43·6	33·8^5	25·8	27·0
Al_2O_3	28·6^5	29·5^5	29·1	33·8^5	29·1	20·7	27·3	19·0	20·7^5	19·1^5	18·0	25·5	34·3^5	33·1^5
Fe_2O_3	1·7^5	1·6	2·2^5	1·3	1·6^5	3·4	2·2^5	2·1	3·2^5	2·7^5	1·8	3·0^5	1·9	3·0
V_2O_3	2·2	2·2	1·8	1·9^5	2·2	2·1	2·3	2·1	1·8	2·8^5	1·9^5	2·4	2·0^5	2·1^5
TiO_2	0·6^5	0·6	0·7	0·2	—	—	0·1^5	0·2	0·1^5	0·1^5	0·6	—	—	—
FeO	25·5^5	25·1	26·8^5	26·2	26·7^5	28·0	26·6^5	28·0	26·9	27·2	28·7^5	30·4	30·0	28·6
MgO	7·2	7·5	6·2	6·5^5	5·3	3·5	5·4	3·6	4·4	4·2	3·5	2·9	4·0^5	5·0
MnO	0·3	0·3	0·3^5	0·3	0·3	0·5	0·5	0·5	0·5^5	0·6	0·5	0·4^5	0·4^5	0·4^5
ZnO	0·8	0·8	0·7^5	0·9^5	1·0	0·9	0·7	1·0	1·0	1·0	0·9	0·5^5	0·7	0·6
NiO	0·1	0·1	0·1	0·2	0·2^5	0·2	0·3^5	0·4	0·1	0·2	0·2	tr.	tr.	tr.
CoO	0·1	0·1	0·1	0·2	0·2	0·2	0·2^5	0·2^5	0·2	0·2	0·2	tr.	tr.	tr.
Sum	100·7	100·5	99·6^5	100·3^5	99·6^5	99·2^5	100·2	100·3^5	99·5	100·3^5	100·0	99·1	99·3	99·9^5
Atomic ratios on a basis of 3 cations:														
Fe^{2+}	0·64^5	0·63	0·68^5	0·66^5	0·70^5	0·78	0·70	0·77	0·74	0·74^5	0·78^5	0·83	0·78	0·74
Mg	0·33	0·34^5	0·29	0·30	0·25	0·17^5	0·25^5	0·18	0·21^5	0·20^5	0·17^5	0·14^5	0·19	0·23^5
Mn	0·00^5	0·00^5	0·01	0·00^5	0·01	0·01^5	0·01^5	0·01	0·01^5	0·01^5	0·01	0·01	0·01	0·01
Zn	0·02	0·02	0·01^5	0·02	0·02^5	0·02	0·01^5	0·02^5	0·02	0·02^5	0·02	0·01^5	0·02	0·01^5
Ni	—	—	—	0·00^5	0·00^5	0·00^5	0·01	0·01	0·00^5	0·00^5	0·00^5	—	—	—
Co	—	—	—	0·00^5	0·00^5	0·00^5	0·00^5	0·00^5	0·00^5	0·00^5	0·00^5	—	—	—
(Ti,Fe^{2+})	0·03	0·03	0·04	0·01	—	—	0·01	0·01	0·01	0·01	0·03	—	—	—
Fe^{3+}	0·04	0·04	0·05^5	0·03	0·04	0·08^5	0·05	0·05^5	0·08	0·06^5	0·05	0·07^5	0·04^5	0·07
V	0·06	0·06	0·04^5	0·05	0·05^5	0·05^5	0·06	0·05^5	0·05	0·07^5	0·05	0·06	0·05	0·05^5
Al	1·05	1·07	1·08	1·22	1·08^5	0·81	1·02	0·74^5	0·80	0·75	0·71	0·98^5	1·26^5	1·21^5
Cr	0·82	0·80	0·78	0·69	0·82	1·05	0·86	1·13^5	1·06	1·10	1·16	0·88	0·64	0·66

1, 2, 3: Chromites in polygonally textured aggregates, La Gallega G 13, G 14.
4 to 8: Chromites in polygonally textured aggregates, Los Jarales Car 32.
9, 10, 11: Skeletal chromites, Los Jarales Car 9, Car 32.
12, 13, 14: Chromites in cordierite rock, La Gallega G 20.

containing an average of 4·2 wt % FeO, 11·0^5 wt % MgO and 0·2 wt % Na_2O (table II). Cordierite crystals showing euhedral growth zones with chromite inclusions show a homogeneous composition of the cordierite and chromite in successive zones. However, some skeletal chromites show differences in composition between the outer frame (analysis 13) and Cr_2O_3- and FeO-richer patches in the skeletons (analysis 12, fig. 4).

TABLE II. *Analyses of cordierite from Los Jarales and La Gallega*

	1	2	3
SiO_2	49·6^5	49·4	—
Al_2O_3	33·9^5	33·6	—
Cr_2O_3	< 0·0^5	—	—
FeO	2·2*	5·3	4·2
MgO	11·5†	10·2	11·0^5
Na_2O	0·7	—	0·2
H_2O	—	1·5	—
	98·0	100·0	

1. Magnesian cordierite $Na_{0\cdot135}$ ($Mg_{1\cdot725}$, $Fe_{0\cdot185}$) $Al_{4\cdot025}$ $Si_{5.000}$ $O_{18\cdot015}$, Los Jarales Car 32. Wt % metals determined by microprobe and calculated into wt % of corresponding oxides.
2. Magnesian cordierite, La Gallega, Hernandez-Pacheco (1967).
3. Microprobe partial analyses of cordierite from La Gallega.

Distortion indices (Miyashiro, 1957) determined on cordierites from Los Jarales and La Gallega range from $\Delta = 0\cdot25°$ to $\Delta = 0\cdot30°$.

* Range 2·0 to 2·4. † Range 11·1 to 11·7.

At Los Jarales the chromites in polygonally textured aggregates show a considerable range in composition as shown by analyses 4, 5, and 6 (table I, fig. 4) of fairly homogeneous grains and by analyses 7 and 8 of the darker core and lighter rim of an inhomogeneous grain, respectively. The chromite skeletons in the same rocks of Los Jarales (analyses 10 and 11, table I, fig. 4) and euhedral crystals (analysis 9) show little variation in composition and appear relatively high in Cr_2O_3 and FeO and low in Al_2O_3 and MgO. The chromites of Los Jarales have *a* 8·232±0·002 Å to 8·239±0·002 Å with a mean value of 8·235±0·002 Å. Cordierite from Los Jarales is somewhat more magnesian than that from cordierite rocks of La Gallega (table II). Brown mica of Los Jarales contains about 1·0 wt % Cr, 0·5 wt % Ni, 0·4 wt % V and traces of Zn and Co.

The skeletal and euhedral chromites of Los Jarales show a specific composition (28±2 mol. % Cr_2O_3, 19±2 mol. % Al_2O_3, 39±2 mol. % FeO, 9±2 mol. % MgO) and have probably crystallized later than the polygonal chromites in the same rocks, which generally appear lower in Cr_2O_3 (28 to 17 mol. %) and FeO (39 to 33 mol. %) and higher in Al_2O_3 (19 to 31 mol. %) and MgO (9 to 15 mol. %). This suggests enrichment in Cr_2O_3 and FeO in later stage chromites and presumably the compositional variation of polygonal chromites of Los Jarales (fig. 4) is due to varying degrees of late stage alteration. The polygonal chromites of La Gallega apparently do not show such alterations and maintain a specific composition with 20±2 mol. % Cr_2O_3, 27±2 mol. % Al_2O_3, 33±2 mol. % FeO and 16±2 mol. % MgO. Compared to this composition the chromites in cordierite rocks of the same locality, apart from possible effects of late stage alterations (analysis 12), generally appear lower in Cr_2O_3 (16±2 mol. %) and MgO (10±2 mol. %) and enriched in Al_2O_3 (31±2 mol. %) and FeO

(38±2 mol. %). A comparison of the chromites in cordierite-poor chromite–nickeline rocks of La Gallega, cordierite-rich chromite–nickeline rocks of Los Jarales, and cordierite rocks of La Gallega also shows that with increasing amount of cordierite the chromites become less magnesian and more ferrous.

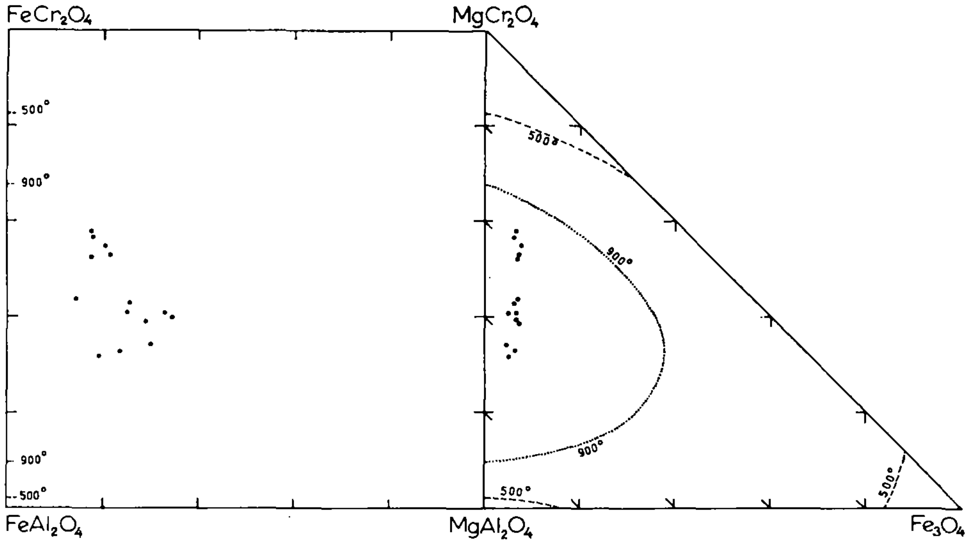


FIG. 5. The figure shows a five-component diagram $FeCr_2O_4$–$FeAl_2O_4$-$MgCr_2O_4$–$MgAl_2O_4$- Fe_3O_4 of the type used in fig. 3. In this diagram the miscibility curves at 900 °C and 500 °C in the system $FeCr_2O_4$-$FeAl_2O_4$-Fe_3O_4 (Cremer, 1969) are plotted. As far as this ternary system is considered the vertical $FeCr_2O_4$–$FeAl_2O_4$ and $MgCr_2O_4$–$MgAl_2O_4$ axes in the figure may be thought to coincide, so that the triangular right-hand part of the diagram may be thought as portraying phase relations in the ternary $FeCr_2O_4$ $FeAl_2O_4$–Fe_3O_4 system. When Mg is present solubility in the five-component system will increase with Mg-content and the 900 °C and 500 °C immiscibility gaps indicated on the vertical $FeCr_2O_4$–$FeAl_2O_4$ axis might be conjectured to extend to the right into the Mg-bearing field in a dome-like form. Dots represent chromite analyses from La Gallega and Los Jarales; they appear sufficiently ferrous-rich to fall within a conjectured dome-like 900 °C immiscibility area in the Mg-bearing part of the diagram. The 900 °C immiscibility area in the right-hand triangle of the diagram will shrink with increasing Mg-content. Again, the chromite analyses from La Gallega and Los Jarales plot sufficiently centrally in the ternary 900 °C immiscibility region that they may be conjectured still to fall within the immiscibility region when the shrunken solvus in the Mg-bearing system is considered.

Conclusions

The genesis of the Cr-Ni-ores of La Gallega and Los Jarales is presumably linked with the petrogenesis of the alpine type ultramafics in which they occur. During emplacement of ultramafic masses in the earth's crust the rocks suffer metamorphic and tectonic reworking, which might lead to re-emplacement (Thayer, 1969, 1970) or new formation of chromite concentrations. The composition of chromites should provide information on the physicochemical environment of (re)crystallization of chromite-bearing rocks, but with limited experimental data available, conclusions must be restricted to a few general inferences.

In the system $FeCr_2O_4$–$FeAl_2O_4$–Fe_3O_4 (Cremer, 1969) there is complete miscibility above 950 °C; below this temperature a large miscibility gap separates the Cr-rich from the Al-rich members in the system (fig. 5). The system $MgCr_2O_4$–$MgAl_2O_4$ is completely miscible at temperatures as low as 510 °C (Warshaw and Keith, 1954) and the presence of Mg in the ferrous system will, therefore, narrow the miscibility gap. The chromites from La Gallega and Los Jarales are sufficiently ferrous-rich to allow comparison with phase relations in the ferrous system (fig. 5). These chromites plot well within the 900 °C immiscibility region and must have crystallized above that temperature. This conclusion seems trivial inasmuch as chromite generally crystallizes at such high temperatures, but it is of significance in the context of the association with cordierite, which is usually formed as a metamorphic mineral below 900 °C, and with Ni-arsenides, which usually crystallize hydrothermally much below 900 °C.

The chromites associated with much Mg-cordierite appear less magnesian; this suggests contemporaneous formation of the ferrous-richer aluminous chromite and magnesian cordierite, whereby MgO and FeO are consistently partitioned over the two minerals. Experimental evidence shows that at high temperature the upper pressure-stability limit of Mg-cordierite decreases rapidly from about 10 kb at 950 °C to below 5 kb above 1100 °C (Schreyer, 1967). At pressures of 10 kb the upper temperature stability limit of phlogopite lies at about 1300 °C (Yoder and Kushiro, 1969). Thus, 1300°–1000 °C seems a fair estimate of the crystallization temperatures of the chromite–cordierite–red-brown mica paragenesis; maximum pressures of formation were below 10 kb and presumably near 5 kb, which implies that the deposits presumably crystallized subsequent to the emplacement of the alpine type ultramafics into a crustal setting.

The assumed crystallization temperatures are within range of liquidus temperatures at the assumed pressures for chromite, cordierite, and brown mica; the arsenides and sulpharsenides have been shown to have unusual composition suggesting crystallization of nickeline above about 700 °C, near its liquidus temperatures (Oen, Burke, Kieft, and Westerhof, 1971). The conclusion seems reasonable that the chromite–nickeline–cordierite–mica paragenesis is derived from a magma of peculiar, highly differentiated composition, with relatively high concentrations of water and such elements as Cr, Ni, Co, Zn, As, and V. The origin of this magma will not be further discussed here. Textural evidence suggests that following the magmatic crystallization of the bulk of chromite and silicates a recrystallization of chromite in polygonally textured aggregates took place, followed by fracturing and the formation of skeletal crystals of late chromite and, at a later stage of cooling beginning at about 800 °C, by the solidification of the interstitial Ni-arsenides.

Oxygen fugacities have a controlling influence on the chromite composition (Irvine, 1965, 1967). The stability of chromite at different oxygen fugacities at 1300 °C has been studied by Ulmer (1969); at this temperature FeO-rich low-ferric chromites become stable at lower oxygen fugacities of the order of 10^{-7} bar; at still lower oxygen fugacities of the order of 10^{-9} bar only FeO- and Cr_2O_3-rich low-ferric chromites can exist (fig. 6). The FeO-rich chromites of La Gallega and Los Jarales have constantly low Fe_2O_3-content of about 1·5 mol. % and were presumably formed at relatively low oxygen fugacities. The enrichment in Cr_2O_3 and FeO in skeletal crystals of late chromite is presumably related to a further decrease in oxygen fugacities as consolidation of the rocks neared its completion.

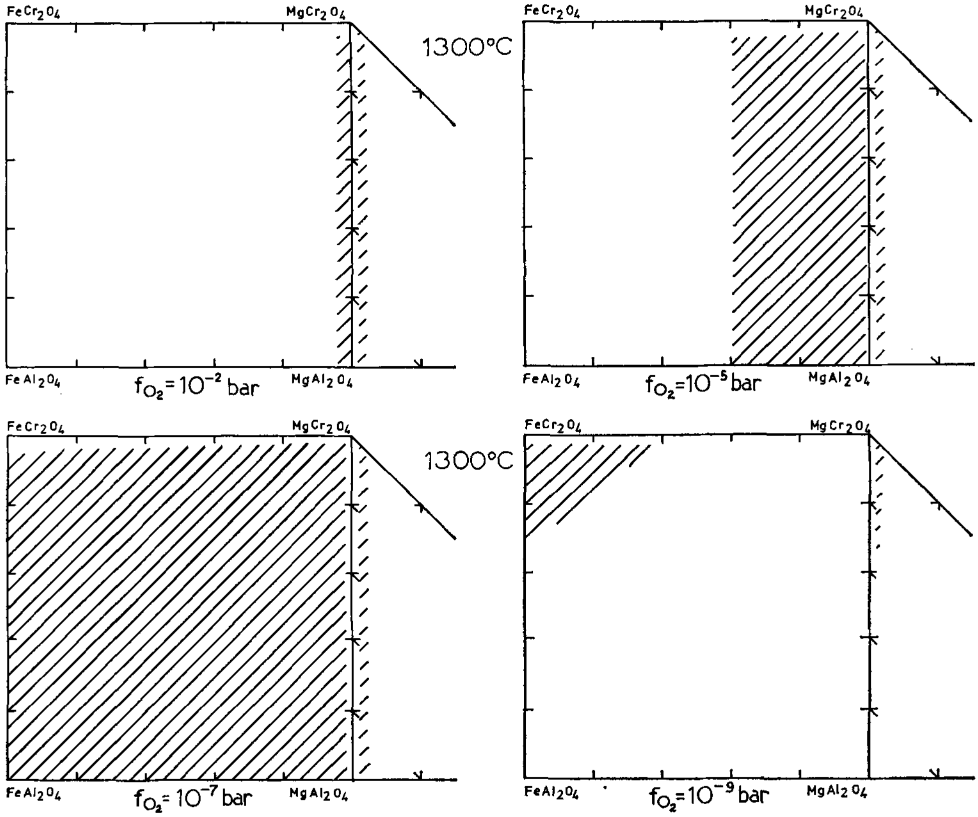


FIG. 6. Approximate compositional ranges of chromite containing 1 to 2 mol. % Fe_2O_3 at 1300 °C and different oxygen fugacities. The diagrams are sketches derived from Ulmer's (1969) figures and have only qualitative value. At high oxygen fugacities only very magnesian chromites are stable. Most naturally occurring chromites have compositions consistent with a formation around 1300 °C and oxygen fugacities between 10^{-5} and 10^{-7} bar; at still lower oxygen fugacities only FeO- and Cr_2O_3-rich chromites are stable.

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